Borehole Mining of Manganese in Emily, Minnesota

A half-road to success

Gregory Abramov
Borehole Mining International, Inc.

Borehole Mining International, Inc., Denver, CO is an independent consulting company specializing in the business of borehole mining (BHM). The author has been involved in BHM since the early 1970s. A previous, most similar to the Cuyuna Range manganese project in Emily, MN, was BHM of oxidized iron ore at the Kursk Magnetic Anomaly, Russia at depths of 800-880 m (2600-2900 ft). The proof-of-concept demo-trial at Emily was successful. However, the project was terminated prior to development of commercial-scale BHM parameters. This article describes the BHM trial, its results, certain problems encountered and potential solutions.

Introduction

Borehole mining (BHM) is a remotely operated mining method based on in-situ waterjetting of an ore, creating slurry which is continuously pumped to the surface. Cuttings are then separated from the slurry, and process water is clarified and recycled. Primary advantages of BHM relative to the conventional mining methods include: minimal environmental impact, simple operating infrastructure, minimal or negative net water use, short time to production, personnel safety and low mining cost. At the sane time, a major limitation of BHM is an inability to mine hard or highly consolidated ores. Certain techniques, such as small-scale blasting, may assist to extend BHM application to those stronger strata, but monolithic hard-rock ores are not amenable. The method is generally applicable to friable, unconsolidated ores, especially those with a tendency to cave- or flow-in when an enlarged diameter cavity (stope) is created downhole.

If surface subsidence is unacceptable, production boreholes are drilled using a pattern which allows for formation of adequate between-the-stopes pillars, similarly to the various underground mining methods. Subsidence is also prevented by emplacement of backfill following BHM ore extraction, assuming the stope will remain open for sufficient time to be able to accept the filler. Finally, using a cement-based backfill material allows BHM stopes to be cut back-to-back, thus increasing the overall mining recovery rate without compromising caprock stability.

Project history

In June 2009, Borehole Mining International, Inc. (BHMI) signed a Demo-trial and Consulting Agreement with Cooperative Mineral Resources (CMR), to provide assistance with a trial of the BHM technology for use at the Emily iron-manganese (Fe-Mn) oxide deposit. An on-site

screening and water clarifying process plant was constructed to sort, classify, dewater and store ore for shipment, in addition to providing high-pressure pumping equipment and related filtration, piping and controls for recirculating water to the BHM tool. A bulk sample of the produced ore was shipped to a laboratory for metallurgical testing in order to define a commercial process for producing salable manganese metal and/or electrolytic manganese dioxide.

Initial data (as of late 2009)

Original mineral exploration of the Emily's Fe-Mn deposit was completed by magnetometer (dip needle) technology, followed by core drilling by the Pickands Mather company during the 1950's. Resulting small-diameter core and subsequent evaluation indicated presence of continuous Fe-Mn mineralization of potentially mineable thickness. However, the company determined that conventional mining methods were uneconomic at that time, and sold the property to a local individual. That small-diameter core was preserved by the new owner, but was inadequate for detailed ore characterization due to almost total loss of the unconsolidated intervals of high-grade manganese core during drilling. A larger, 4-inch nominal diameter (102 mm) drill core was obtained in the middle of the 90s by sonic drilling. This method enabled nearly 100 percent core recovery and provided intact intervals of high-grade manganese mineralization suitable for preliminary ore characterization (e.g., degree of consolidation, particle size, density, etc.) for mining purposes. The Emily deposit subsequently came under control of CMR. Suitability for the BHM method at the Emily site was determined based on examination of those core samples by CMR's consultants and BHMI personnel.

The following observations were made related to the BHM test site:

- Groundwater surface is located at approx. 12 ft (3.6 m) depth;
- Approximately 180 ft (54 m) of glacial till overlies the ore-bearing formation;
- Ore physical properties such as hardness, stability, etc. (as evidenced by observation of the sonic drill core) vary from friable and unconsolidated and likely to cave (majority), to hard, stable and unlikely to cave (minor amount);
- The highest manganese grade and most unconsolidated ore interval is 57 ft (18 m) thick, located in the 335 ft to 392 ft (102 m to 120 m) interval at the proposed BHM test well site;

Based on these observations, a depth of 397 ft (121 m) was selected as the starting point for the initial BHM trial. It was expected that, while undercutting the ore at that depth, the overlying ore would periodically collapse into the created void, be further disaggregated by the waterjet and removed to the surface by the BHM tool.

For the trial, BHMI designed and manufactured an 8-5/8 in (219 mm) OD BHM tool, presented in Fig 1.

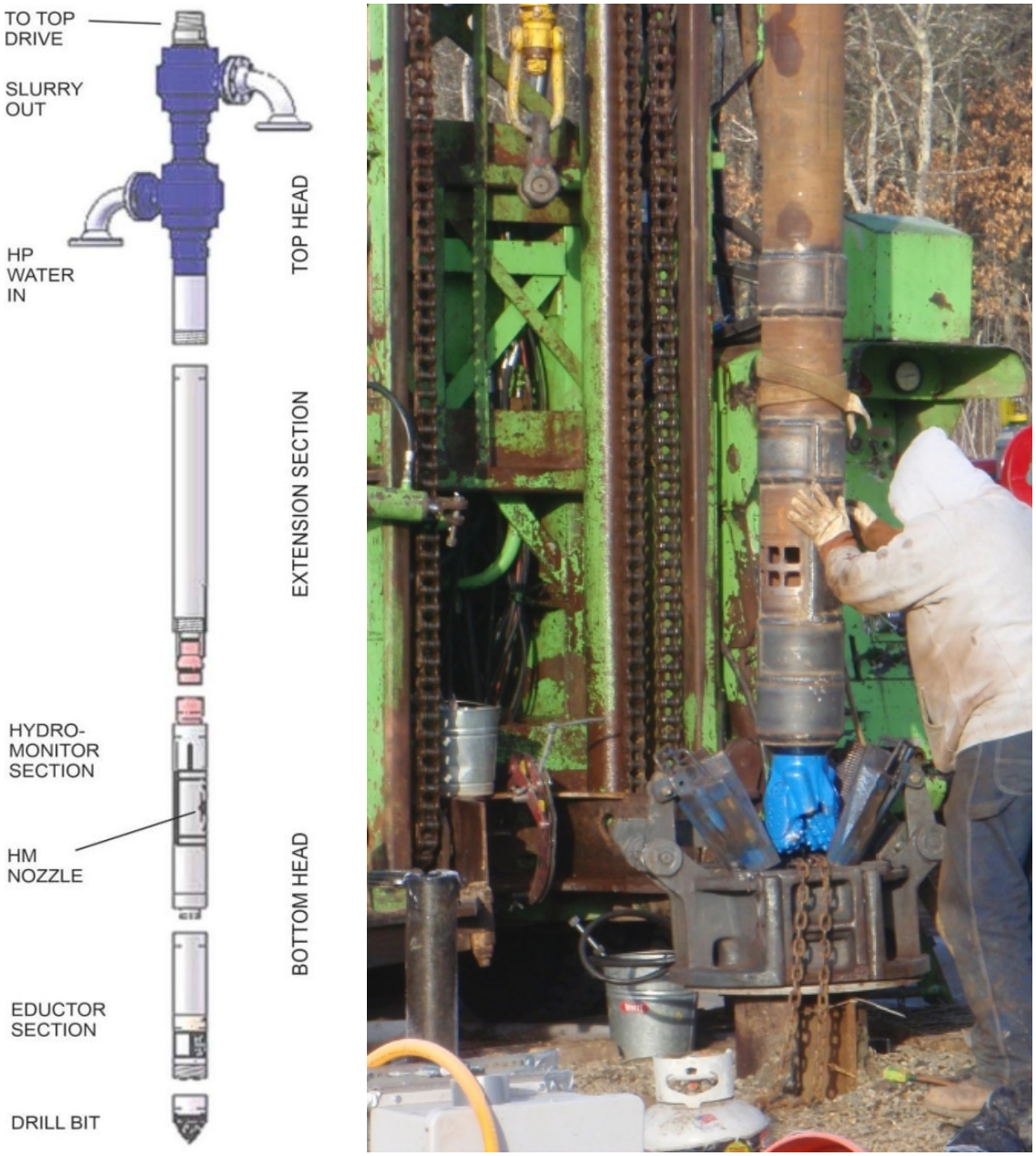

Fig 1. BHM tool 3D CAD model exploded view and the Bottom Head being lowered into the well.

A 12-in. (305 mm) borehole was drilled for the BHM test to a depth of approximately 410 ft (125 m) to the bottom of the known ore interval. Fourteen inch (356 mm) well casing was cemented through glacial till to 180 ft (55 m) depth and a protective temporary 10” (224 mm) well casing was set to 345 ft (105 m) depth through an overlying high-grade ore interval to prevent caving above the initial BHM test zone.

The BHM demonstration started in late 2010 and, with multiple interruptions, lasted for about 8 months. Other than weather conditions and national holidays, these interruptions were caused by technical issues such as:

- BHM tool eductor blockage by large and mid-size ore particles (see Fig 8, right) followed by the tool removal, cleanup and reassembly;
- BHM tool extension section parting and being lost downhole, followed by its “fishing out” recovery, repair and re-attachment to the extension section;
- BHM tool swivel high pressure (HP) gasket failure and repair;
- HP pumps overheating and corrective modification;
- BHM tool slurry hose connection failure and repair;
- Various processing plant malfunctions and related delays;
- Abrasive wear in the test site-to-plant slurry pipeline.

In Fig 2, the 8-5/8” BHM tool in operating position is shown.

Fig 2. Upper Head of the BHM tool showing dual swivel and water/slurry hoses.
CP-700/7000 drill rig was modified by addition of a low-speed gearbox to the rig’s top drive head.

Slurry processing

From the tool's discharge hose, ore slurry went to a coarse grizzly screen (Fig 3) where all particles ¼-in. (6.4 mm) and larger were rejected and collected in an oversize ore bin (Fig 4). Fig 5 shows examples of some largest oversize particles produced by the 8-5/8" BHM tool.

Fig 3. Grizzly screen with oversized ore and waste particles.

Fig 4. ¼-in. and larger material in the oversize bin.

Fig 5. Some large particles in the oversize bin.

All particles passing the grizzly screen were pumped to the processing plant as a slurry. At the plant, the slurry went through several screens, a series of filters, clarifiers, cyclones, and other sorting and processing equipment. The slurry was then dewatered and filtered, clarified water went to the HP pump station and was recirculated to the BHM tool. In Fig 6 a, b and c, the resulting Fe/Mn processed ore size fractions are shown.

Fig 6a. Clay-size (front) fractions collected separately from the rest of the ore.

Fig 6b. Mid-size ore fractions. A front loader and haul truck shown in the rear.

Fig 6c. The first batch of a high-grade coarse-size Manganese Ore.

Fig 7. presents the largest particles of Manganese ore recovered by the BHM tool.

Fig 7. Oversized particles of Mn ore. Particle #9 measures up to 3-in.

Abrasive wear

Emily Manganese ore demonstrated extremely high abrasiveness. In Fig 8, the BHM tool eductor grill abrasive wear is illustrated.

Fig 8. The same slurry grill shown new (left – before use), and heavily worn (right) after a few weeks of use.

In Fig 8 (left), several previously recovered large ore particles were manually placed in the Grill to compare them with the grill openings size. The right photo illustrates some ore particles settled in the BHM tool and completely plugged the eductor following sudden loss of HP water circulation due to a process water system malfunction. This event required removal of the BHM tool from the well, tool disassembly, cleaning and replacement in the well. To avoid such drawbacks, the pump(s) and all other equipment should be well controlled and maintained. Ideally, BHM operations should continue non-stop. Several other areas of the tool exposed to

the ore were also found to suffer from abrasive wear. The tool was constructed of mild steel; to extend its life, more abrasion-resistant materials are recommended.

Mining 24/7 and year-round

Since only a few personnel are typically required to operate the BHM tool, it is worthwhile to run BHM operations non-stop, 24/7. In Fig 9, BHM tool operation is shown during a night shift (left) and below-freezing temperatures.

Fig 9. Borehole mining 24/7 and at sub-freezing temperatures.

Slurry exiting the borehole was constantly above freezing temperature, at some 45-50ºF (7-10ºC). However, to prevent freezing of the surface slurry and HP water pipelines, especially during winter nighttime operations, a thermo-blanket was used as shown in Fig 10. The blanket covered both pipelines for the entire distance from the HP pump station to the BHM site and incorporated ethylene glycol warming and circulation equipment.

Fig 10. Thermo-blanket covering HP water (right) and slurry (left) pipelines.

Water overproduction and Pinch Valve

The water IN and slurry OUT pipelines were equipped with pressure gauges and flow meters. Their readings were added to the BHM site WiFi network, which made this data available in real time at the process plant, high-pressure pump installation and the well site. Fig 11 shows one of the process fluids monitoring and control panel.

Fig 11. Pressure, flow, & other BHM and process parameters display/controls at the mining site.

Initial BHM system operation demonstrated that the BHM tool overproduced slurry at a rate approximately 10-12% greater than the volume of HP water being pumped into the well. As a submerged waterjet quickly dissipates, its cutting effectiveness is best when the cutting radius is just a few inches, resulting in production of the greatest slurry density. Further, as the cutting radius increases, the jet effectiveness and slurry density decrease. However, the eductor production capacity remains unchanged (assuming HP water flow and pressure are unchanged). To accommodate such slurry density fluctuations, the tool is designed for the maximum slurry density expected, by using the adequate eductor's Venturi and nozzle parameters. Regardless, when slurry density decreases, the eductor produces a larger flowrate. Eventually, the eductor may produce more fluid than the volume of HP water supplied to the tool, resulting in the fluid overproduction. In such a case, it oftentimes results in the producing of groundwater from the mined formation. Additionally, slurry density spikes occur due to sudden caving of the stope's walls or roof. Once again, this is why an eductor is designed to accommodate such spikes. In BHMI's nearly 55 years of experience, any fluid overproduction was always a positive factor for mining efficiency; the more productive the eductor's performance, the better. However, this is not an advantage in the State of Minnesota, where disposal of excess groundwater is a potential environmental issue.

To prevent this water overproduction, the engineers working on-site suggested that an automated pinch valve be installed just downstream of the BHM tool slurry outlet hose. This valve would automatically decrease ("pinch") the diameter of the slurry pipe without

excessively impairing slurry flow. This flow reduction caused an increase of the back-pressure in the slurry line and resulted in the reduction of the slurry flow rate. The amount of valve closure (pinching) was automatically controlled (using the data from the flow and pressure sensors) as the slurry flow rate fluctuated to above-acceptable levels.

This technique balanced the slurry production rate, thus solving the problem. However, the reduced slurry flowrate imminently resulted in reduction of the eductor's suction ability and efficiency, impairing recovery of some large and mid-size ore particles, which were left at the bottom of the stope. It finally increased the overall water pumping energy consumption per produced unit of slurry. To dispose of excess produced water in an environmentally acceptable way, an electro-mechanical evaporator or other evaporation systems could be recommended.

Waterjet cutting nuances and test results

Any waterjet has a critical distance called the maximum cutting reach radius. Beyond it, the jet becomes too weak to continue to effectively cut the ore. If this happens before the created stope caves in, produced slurry density is quickly reduced to zero, and ore recovery stops.

The BHM trial demonstrated that Emily ore hardness and stability were underestimated. As a result, ore caving occurred less extensively and frequently than anticipated, causing reduction of overall BHM efficiency. This led to on-site experimentation with various techniques to improve jet cutting effectiveness and slurry density. One such technique was to simply raise the tool to a new depth to start cutting ore in an unmined interval located above the present stope.

Below, the technical results of the BHM Demo-trial are presented:

- Total number of truckloads shipped: 30 loads @ 20 short tons per load;
- Total ore weight shipped: 600 short tons (546 tonnes);
- Total ore volume: 400 yd^3 (305 m^3);
- Total jetting time: 200 hours (25 workdays);
- BHM productivity: 2 yd^3/hour (1.5 m^3 /hour).

Knowing that all the cutting took place within an approx. 96 ft (~30m) vertical interval, the 400 yd^3 stope would average 13 ft (4m) in diameter. In the reality, the shape of the stope was probably more like a Chinese lantern with diameter variations from 1ft (diameter of the open hole) to 16–20 ft (5-6 m) or possibly greater, depending on the variation of the ore consolidation and hardness within the mining interval. Regardless, the irregular shape did not affect the stope stability. It remained open, as there was no indication of surface subsidence, as evidenced by ongoing subsidence control and measurements by the existing monitoring network, for an extended time following termination of BHM operations.

Obviously, the 13 ft (4 m) diameter stope, as well as 1.5 m^3 /hour ore production rate are inadequate for a commercial borehole mining operation. Typically, these numbers are 26-40 ft (8-12 m) and 20-30 m^3/hour, respectively. Meanwhile, this was not the first time BHMI

experienced conditions of extremely stable ore. One common solution in these cases is to increase the size of the BHM tool and the HP water pumping rate. A stronger waterjet allows cutting of the same ore further from the tool and creates a larger diameter stope, which is more likely to cave.

Another common way to increase a stope diameter is to force it to cave by blasting. This can be done through the same borehole, or better yet, through dedicated blasting holes drilled outside the stope contour. Since only light stress or shaking of the ore is required, the blasting charges are relatively small and usually cannot be heard or sensed on the surface. They also cannot cause any destruction to the strata above and around the stope as all the explosion energy is spent on pushing the ore into the available void. Thus, the effect of stress in the outward direction is minimal or nonexistent.

Increasing the diameter of a stope serves two purposes: (1) to extract more material from a borehole, and (2) potentially reach that critical diameter of the stope at which its walls begin to collapse and cave spontaneously, allowing more material to be extracted. Beyond this point, however, it becomes impossible to create a stable stope (capable of remaining open for a matter of more than a few minutes), making backfill impossible. If backfill is required in order to prevent the surface subsidence or complete collapse of the well, the stope should not exceed that critical diameter. If the critical diameter is exceeded, the only way to stop caving and prevent subsidence is to immediately discontinue mining operations and remove the tool from the well.

It is important to point out that the critical diameter of a stope, beyond which caving-in occurs immediately, is impossible to accurately determine using mathematical equations or computer modeling; only field tests give a precise answer. The Emily BHM demo-trail indicated that the average 13 ft stope diameter did not exceed that critical diameter, and it remained open for an extended time. The next step for this project would have been blasting or a larger BHM tool, as described above. At that time, however, the project was indefinitely terminated.

Meanwhile, the BHM trial at Emily not only delivered a bulk ore sample to the lab test program, but created a stope ready for backfill, which could have demonstrated that additional element of the BHM process. If continued to a conclusion, and assuming only a small percentage of the ore was too hard or consolidated to be recoverable by BHM methods, the Emily BHM technology may have been subsequently developed into a commercially-viable mining method for this deposit.

Questions left unanswered

Obviously, the development of the entire Fe-Mn orebody will require numerous boreholes. To proceed to this stage, the following major questions would have to be answered:

- Optimal distance between the boreholes, their pattern and total amount;
- How many BHM tools will be required to work simultaneously and in which sequence they will be moved from one borehole to another;
- Where mining should be started, in which direction(s) it should progress and where be

ended;

- Backfill technology procedures and equipment required;
- What time will it require to develop the entire deposit and what will it cost.

These and other questions could be answered within 3-5 years (around 2015). During this development time, the mine would continue producing the ore and, at least partially, reimburse the required investment. Due to the early termination, Emily's BHM project never approached these questions, even distantly.

BHM demo-trial results

1. Emily ore hardness, abrasiveness, stability and variations in consolidation are greater than previously assumed;
2. Despite the ore excessive abrasiveness, the BHM tool and technology demonstrated stable performance;
3. As planned, a bulk sample of the ore was extracted and delivered to the lab for testing and experimentation;
4. BHM at below-freezing temperatures, up to -25 F (-32 C), has been demonstrated;
5. BHM technology demonstrated its applicability for mining of Emily's Fe/Mn oxide ores. To achieve commercial rates, the technological parameters require further development, including higher waterjet pumping rates and/or assisting with the ore blasting. Additional testing would be required to determine these parameters;
6. Further development of BHM technology required subsequent proceeding from a single borehole demo-trial to multi-well commercial-scale mining operations;

The test was terminated prior to alterations to the BHM technology suitable to overcome the revealed problems.

Conclusion

Even such well-known and widely used mining methods as room-and-pillar, cut-and-fill, etc. are not "plug-n-play" technologies. It's impossible to simply apply them in a mine design and expect immediate commercial success. Extensive field trials, R&D, experimentation, etc. are normally required to optimize a selected technology to encompass a deposit's geology, hydrogeology, ore physical properties and many other parameters. More than that, if one or more geological, hydrogeological or other parameters change within the same orebody, it may and, more likely, will affect the nuances of the chosen technology, requiring its additional (this time on the go) experimentation and adjustments, again.

Borehole mining is not an exception. It would be unrealistic to expect a preliminary proof-of-concept BHM demo-trial to yield the optimal combination of BHM equipment and operational parameters for immediate application to a commercial mining operations. Especially for the mining project magnitude as Cuyuna Range Fe-Mn ores. Unfortunately, instead of optimization of the technology, BHM was scrapped altogether at half-road to success.

The BHM trial demonstrated that subsoil high saturation and permeability, ore thickness and depth, as well as its wide variety of physical properties, make conventional mining at Emily expensive, dangerous, environmentally problematic and likely difficult and time-consuming to permit. Meanwhile, manganese remains 100% imported to the US mostly from S. Africa, Gabon, Australia, India, and China, the top-5 world producers of this strategically important metal. It is sad to contemplate the ongoing large cost of these imports and related supply chain dependency of the US economy while the Emily deposit remains untapped for decades.

Borehole mining does not replace conventional mining methods. In majority cases, these technologies are preferable. But there are circumstances when BHM becomes more attractive. Generally speaking, conditions which make conventional mining difficult or very expensive, oftentimes present opportunities for alternative mining methods, such as BHM. It is the author's strong opinion that, properly developed, Borehole Mining remains an excellent and, apparently, the only candidate for North America's largest and richest Cuyuna Range Manganese deposit in Emily, Minnesota.

Acknowledgement

The author expresses special thanks to Mr. Steve Axen of Ray V. Huff & Assoc., Inc. for his assistance and review of this article.

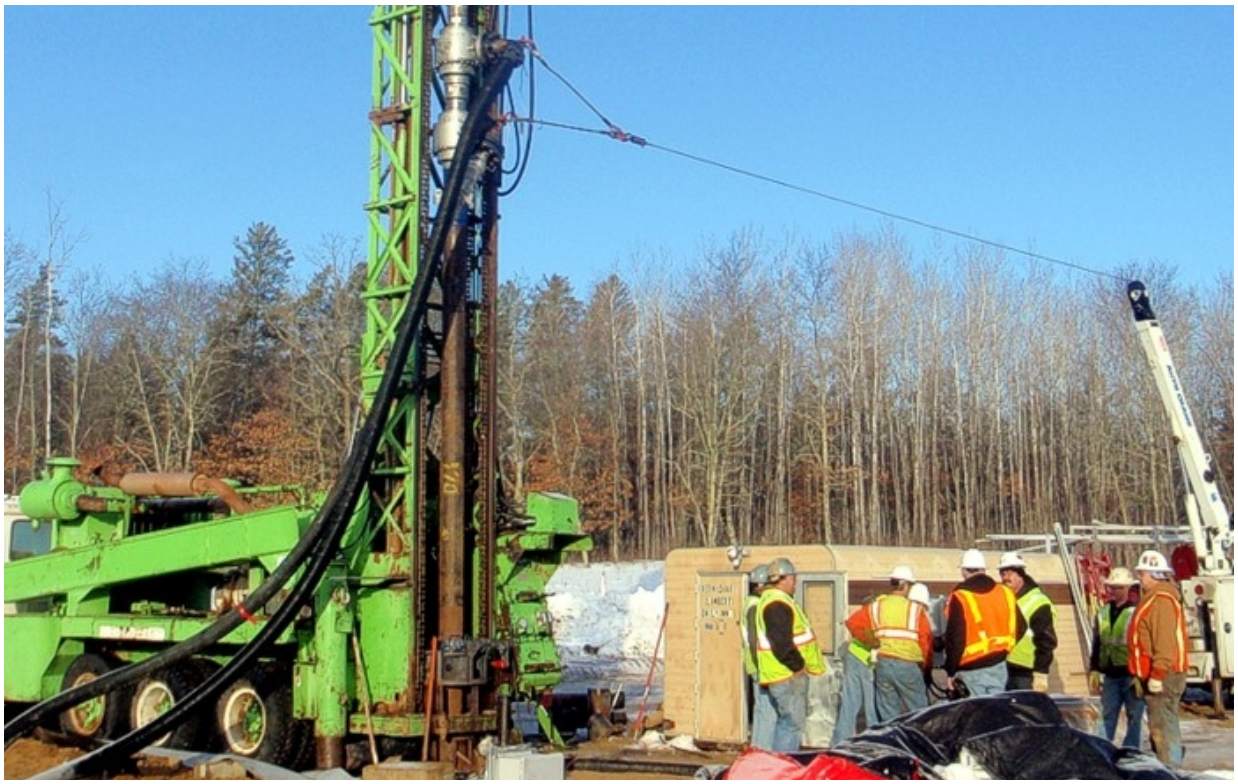

Fig 12. Emily, MN borehole mining demo-trial site and BHM Team-2011.